

# PROTECTION FUSE FOR A 4.5 MJ CAPACITOR BANK

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Fusible protection elements have been developed for the 4.5 MJ, Pegasus-II capacitor bank. These fuses are designed to prevent voltage swings of greater than 120% of the maximum capacitor charge voltage--the maximum permitted reversal is the actual charge voltage minus 1.20 times the maximum allowed charge voltage. This is accomplished without significantly degrading the current wave form except near  $T_{1/4} = \pi/2\sqrt{LC}$ . A major portion of the capacitor bank stored energy is dissipated in the protection elements, and the voltage during the interruption process is kept as low as possible--unlike for high-performance, opening-switch fusible elements.

## I. Parameters of Test Circuit and Fuses.

To date, 12 shots have been made on the Pegasus-II capacitor bank at charge voltage from 39 to 88% of maximum allowed charge voltage. Development tests of fuse performance on a 1/144 scale model of Pegasus-II are described below. These tests utilize an array of medium-energy-density capacitors which are tolerant of voltage reversal, and able to be charged to 20% higher voltage than the Pegasus-II capacitors. A net capacitance of  $6.4 \mu F$  is switched into an inductor of  $2.7 \mu H$  to give a quarter cycle time of 6.55 usec (other values of inductance and rise time are available). The design of the insulator, single-detonator switch system and transmission lines are almost identical to Pegasus-II. A typical fuse element in the test facility is .0005" thick aluminum foil, 2.4" wide and 40" long and the insulation-pack is 0.3 to 0.5 inches thick. Choice of fuse dimensions and material is discussed in detail below. Initially, at room temperature, the fuse resistance is  $\ll$  the characteristic circuit impedance,  $\sqrt{L/C}$ , and the fuses are operated over a range of  $\sim 100:1$  in resistance.

The procedure for determining the fuse dimensions follows Tucker and Toth<sup>1</sup>. The energy of the capacitor bank is to be dissipated near the quarter cycle time,  $T_{1/4}$ , when most of the stored energy is in the system inductance. The time scale for fusing must be much less than  $T_{1/4}$  but large enough that the fuse voltage does not exceed the maximum design voltage of the transmission system,  $fV_0$  where  $f \sim 3$ . We require:

$$\sqrt{LC} \gg L_0/R_{\max} \gg \sqrt{\frac{LC}{2f}}$$

(The maximum fuse voltage is assumed to occur for  $i \sim i_0/2$ ). The above inequality is satisfied for

$R_{\max} = 2f \sqrt{L/C}$ , and the initial fuse dimensions have been chosen such that:

$$R_{\max} \sim 2f \sqrt{L/C} = \rho_{\max} \ell / \text{area}$$

where  $\rho$  is the fuse resistivity,  $\ell$  is the fuse length and "area" is the cross-sectional area of the fuse.

We also require that the fuse dissipate most of the initial energy of the capacitor bank. The dissipated energy is  $\sim 0.75 \times 1/2 CV_0^2$  when the fuse has cut the current to 0.5 of the peak current,  $\sim V_0 / \sqrt{L/C}$  (Efficiency of energy delivered to the load on Pegasus-II is typically 10s of percent). We require:

$$\text{dissipated energy} \sim \text{specific energy} \times \text{density} \times \ell \times \text{area}.$$

The fuse length and area can be determined from the above conditions when the state of the fuse near peak resistance is known--specific energy and resistance at maximum voltage.

In Appendix I the fuse parameters are related to the over-voltage factor  $f$ . Data from Tucher and Toth indicate that for this system the fuses must go to burst--beyond the vapor beginning state.

## II. Insulation and Quenching Configuration

High-density fuse strips are bonded to .015" thick polyethylene sheets for ease of handling. Initial tests utilized a sheet of polyethylene to serve as a tamping material against the foil on the side opposite the substrate. This system was based on the work of V. A. Burtsev, et al<sup>2</sup> with a polyethylene medium surrounding the fuse, and was investigated as a technique to avoid using sand or quartz dust. This configuration resulted in considerable mechanical coupling from the bursting fuse to the insulation system even with cushioning layers in proximity to the polyethylene. Subsequently, the polyethylene tamping layer has been replaced by fine-weave, thin fiberglass cloth. The porous cloth functions similarly to sand as a tamping material and mechanical coupling has been almost entirely eliminated. The remainder of the insulation and cushioning system for these fuses is based on the system used for Shiva Star at the Phillips Laboratory.<sup>3</sup>

## III. Interpretation of Test Data

The resistivity as a function of specific energy, the specific energy and the action,  $(\int (i^2/\text{area}^2) dt)$ , are determined by integrating the current wave forms as measured by Rogowski probes. Voltage probes on the fuses and the capacitor feed plates can be used to confirm the data interpretation. The resistivity is given by:

$$\rho(t) = \frac{\text{area}}{\ell i(t)} \left\{ V_0 - (1/C) \int i dt - L di/dt \right\}$$

The specific energy is given by:

$$E_m(t) = \frac{1}{n_o \text{ area} \times \ell} \{ V_0 Q_e - 0.5 Q_e^2 / C - 0.5 L i^2 \}$$

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Where  $Q_e = \int i dt$  is the charge flowing out of the capacitors,  $V_0$  is the initial voltage,  $i(t)$  is the current,  $L$  and  $C$  are the equivalent inductance and capacitance, and  $n_o$  is the density of the fuse material.

The action is a convenient quantity for fuse design (see Tucker and Toth<sup>1</sup>). It is not an independent characteristic of the material, however, and when  $\rho = \rho(E_m(t))$  can be easily shown (see Appendix II) to be related to the resistivity as a function of specific energy by:

$$Action(E_m) = (n_o / \rho_o) \int dE / (\rho / \rho_o)$$

where  $\rho_o$  is the room temperature resistivity.

#### IV. Test Data

Resistivity data vs. specific energy for a wide range of operating conditions on the 6.4  $\mu F$  test facility and the initial shot on Pegasus II are shown in Figure 1 where the insulation system is the same for all shots. The results of Andrezen, et al<sup>2</sup> for aluminum foil in quartz dust are contained within the lines drawn on the figure. Data of Tucker and Toth are also included. Above  $10^3 J/gr$  most of the data points indicate resistivity near the lower edge of the data of Burtsev. Specific energy is also given for these cases (Figure 2).

This data indicates that for the Pegasus-II quench material—fiberglass cloth and aluminum foil bonded to polyethylene—the resistivity vs. specific energy is close to the data of Andrezen et al, Tucker and Toth, and Burtsev. The somewhat lower values of resistivity may be due to cooling from the intimate contact of the bonding material. Mechanical pressure for this system is  $\sim 1$  psi and is due to the weights utilized to avoid mechanical motion from magnetic pressure. This value of pressure is less than the lowest value given in the analysis of Lindemuth<sup>6</sup>, et al and indicates that the data should be considered unpressurized.

#### Appendix I

The action,  $\int (i^2 / area^2) dt$ , can be related to the conditions for fuse resistance and dissipation by the following approximate analysis. If the current is assumed to be sinusoidal up to the interruption at  $t = T_{1/4}$  then the action at interruption is approximately given by:

$$Action(t = T_{1/4}) = 0.5 CV_o^2 T_{1/4} / (L area^2)$$

which can be expressed in terms of the characteristic impedance of the circuit,  $\sqrt{L/C}$ , as:

$$Action(t = T_{1/4}) = 0.5 CV_o^2 (\pi/2) \sqrt{C/L} / area^2$$

The fuse resistance at maximum voltage is:

$$R_{max} = 2f \sqrt{L/C} \text{ where } R_{max} = \rho_{max} l / area$$

The capacitor bank energy is approximately related to the dissipated energy by:

$$0.5 CV_o^2 = (4/3) \times \text{specific energy} \times \text{density} \times l \times \text{area.}$$

The action can be expressed as:

$$Action(t = T_{1/4}) \sim \frac{(n_o / \rho_o) (4\pi f / 3) \text{ specific energy}}{\rho_{max} / \rho_o}$$

We have taken  $f \sim 3$  to limit the voltage at interruption, and the properties for the fuse material are given by:

$$\left\{ \frac{Action \times (\rho_{max} / \rho_o)}{\text{Specific Energy}} \times (\rho_o / n_o) \right\} = 4\pi f / 3 \sim 4\pi$$

The data of Tucker and Toth for Aluminum indicate that only near "burst" do the fuse properties combine to meet the above condition for this type of system.

#### Appendix II

The action can be related to the resistivity as a function of specific energy,  $E_m$ . The energy dissipated by the fuse is given by:

$$E(t) = \int (i^2(t) \rho(t) l / area) dt$$

The power per unit mass,  $dE_m / dt$  is given by:

$$dE_m / dt = (\rho_o / n_o) (i^2(t) / area^2) \rho(t) / \rho_o$$

This expression can be rearranged and integrated to give:

$$Action(t) = (n_o / \rho_o) \int \frac{dE_m / dt}{\rho(t) / \rho_o} dt$$

Since  $\rho = \rho(E_m(t))$  the action as a function of specific energy is given by:

$$Action(E_m) = (n_o / \rho_o) \int \frac{dE_m}{\rho(E_m) / \rho_o}$$

#### References

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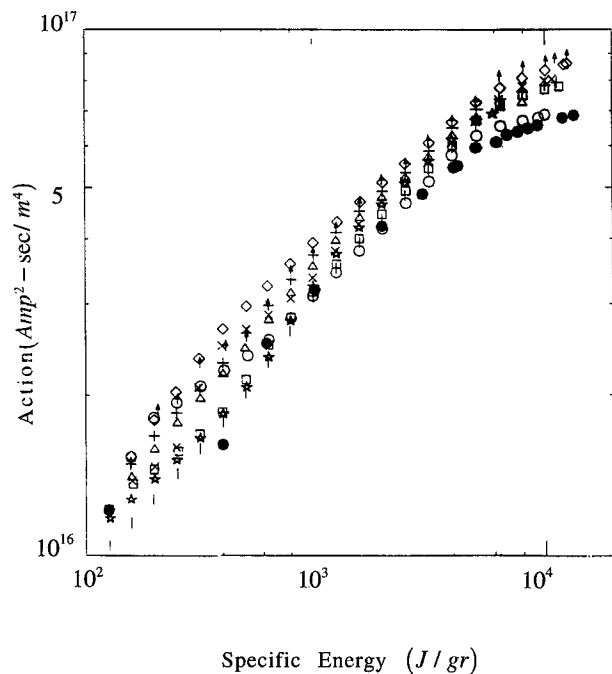


Figure 2: Action vs. specific energy for fuse tests, Pegasus II initial shot and Tucker and Toth (ref. 1) data. Aluminum foil .0005". Other parameters listed in Table I.

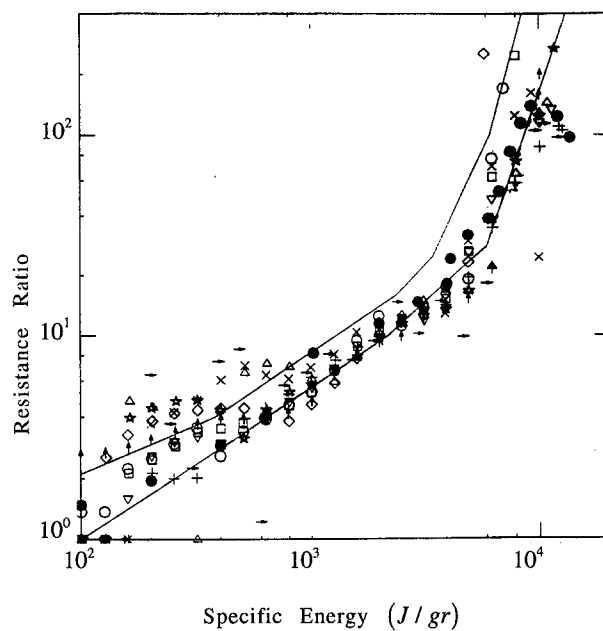


Figure 1: Relative resistance vs. specific energy for fuse tests, Pegasus II initial shot and Tucker and Toth (ref.1) data. Solid lines are upper and lower bounds for the data of Andrezen, Burtsev, et al (ref.2). Aluminum foil .0005" thick. Other parameters listed in Table I.

● Tucker and Toth Data				
○ Pegasus-II Shot 1 data				
× Test bay shot 21.	W = 64mm,	L = 100cm,	I = 119 kA,	V = 84kV
△ Test bay shot 33.	61	100	112	88
□ Test bay shot 34.	41	100	72	60
★ Test bay shot 35.	41	70	74	60
◇ Test bay shot 36.	20	70	33	28
+ Test bay shot 37.	51	100	103	86
↑ Test bay shot 38.	71	100	120	90
▽ Test bay shot 39.	61	100	116	90
→ Test bay shot 40.	48	100	104	90

TABLE I: Parameters for the data in Figure 1 and Figure 2. All shots made with .0005" Aluminum foil.